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Simulated evaluation of an intraoperative surface modeling method for catheter ablation by a real phantom simulation experiment

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Abstract

In this work, we propose a phantom experiment method to quantitatively evaluate an intraoperative left-atrial modeling update method. In prior work, we proposed an update procedure which updates the preoperative surface model with information from real-time tracked 2D ultrasound. Prior studies did not evaluate the reconstruction using an anthropomorphic phantom. In this approach, a silicone heart phantom (based on a high resolution human atrial surface model reconstructed from CT images) was made as simulated atriums. A surface model of the left atrium of the phantom was deformed by a morphological operation – simulating the shape difference caused by organ deformation between pre-operative scanning and intra-operative guidance. During the simulated procedure, a tracked ultrasound catheter was inserted into right atrial phantom – scanning the left atrial phantom in a manner mimicking the cardiac ablation procedure. By merging the preoperative model and the intraoperative ultrasound images, an intraoperative left atrial model was reconstructed. According to results, the reconstruction error of the modeling method is smaller than the initial geometric difference caused by organ deformation. As the area of the left atrial phantom scanned by ultrasound increases, the reconstruction error of the intraoperative surface model decreases. The study validated the efficacy of the modeling method.

Keywords

intraoperative left atrial surface reconstruction; Poisson Equation Reconstruction; intra-cardiac echocardiography; catheter ablation; phantom evaluation

1. INTRODUCTION

2D tracked intra-cardiac echocardiography plays an important role in catheter ablation therapy.[1] However, due to low resolution, it is often desirable to have access to a high fidelity anatomical model during treatment for guidance. Previously, we proposed an intraoperative left-atrial surface modeling method for catheter ablation, which provides an updated 3D surface model by integrating real-time 2D ultrasound data with pre-acquired data such as computed tomography (CT) or magnetic resonance imaging (MRI) data.[2] The validity of the modeling method was proved by virtual phantom experiments. This study aims to quantitatively evaluate the method by real phantom experiment which simulates practical process of catheter ablation.

2. METHODOLOGY

2.1 Phantom Model

Figure 1 shows the atrial phantom built from the CT scan of human atriums. The atriums were surrounded by silicone has similar acoustic property as human tissue and can be imaged with ultrasound. The phantom was then scanned by CT, and a 3D model of the left atrial was built as the true atrial model. Figure 1 (b) shows one slice of the CT scan of the phantom, where the hole on the right side is the entrance of the right atrium for ultrasound to be inserted to scan the left atrium.

2.2 Pre-Acquired Model

Although the intra-cardiac echocardiography is ECG-gated so that the real-time acquired images are in the same phase of an ECG cycle as the pre-acquired model built from CT or MR, however, due to intraoperative changes, noise in the ultrasound acquisition, and registration errors, there is certain difference between pre-acquired model and real left atrium. To simulate the anatomical change between preoperative model and the simulated atriums, we first generate a simulated preoperative model by applying differential contractions and dilations across different parts of the preoperative surface (Fig. 2). The RMS error between the simulated preoperative model and the true atrium can be computed by Hausdorff Distance,[3] which is 1.79 mm.

2.3 Clinical Workflow of Simulation Experiment

The clinical workflow of our proposed experiment is as follows. First, the pre-acquired model was registered to the phantom model by using corresponding point based registration (Fig. 3(a)). Next, we calibrate the ultrasound so that each pixel on the ultrasound image has a corresponding coordinate in the reference frame of the tracking device. The calibration method is detailed in [5]. After calibration, the ultrasound probe is inserted into right atrium of the phantom to image the inner wall of left atrium, which exactly simulates the clinical procedures in catheter ablation. Individual US images of the left atrium are segmented, and the edge contour points are mapped into the 3D geometry of the tracker. The intraoperative point cloud is used to update the preoperative model by using the modeling method previously proposed. (Fig. 3(b)). [6] Then the pre-acquired model was updated and merged by the intraoperative point cloud, with the normal vectors of every vertex estimated. [2] Finally, the updated surface model of left atrium was built by the Poisson Equation (Fig. 3(c)). [7]

3. RESULTS

During the ultrasound calibration, 25 calibration frames were used and the calibration error was 2.40±0.92 mm. In the process of registration of pre-acquired model and phantom model, four registration points were used to compute the transformation matrix and another four target points were used to estimate target registration error, which is 2.21±0.64mm.

In the simulation experiment, 67 frames of ultrasound images were collected. Fig.4 shows the aggregating point cloud as ultrasound continued scanning. The point clouds displayed in Fig. 4a-d are 3D spatial point clouds. Figure 5 renders the point cloud of Fig. 4d in two different views. We can recognize the main body and vascular parts of the left atrium shown in Fig.2 from Fig. 5.

Figure 6 is the intraoperative model built by merging the point cloud of 67 frames (Fig. 4d) and the preoperative model (Fig. 2c). We can see after updating, the merged model has restored to the shape of the true atrium in the area scanned by ultrasound, e.g. the vascular on the left bottom part is dilated compared with the preoperative model. Figure 7 shows the distribution of reconstruction errors of updated model, compared with the true left atrium. As the color turns from blue to red, the reconstruction error increases. The largest error appears on the right top part of the atrium because there is a hole in this part for the true left atrium which is filled in the updated model. Besides, the relatively big error appears in the main body part of the left atrium, however, there are small-error regions scattered in the big-error area where the vertices were updated by the intraoperative ultrasound (white rectangles in Fig. 7), which indicates that our modeling method could reduce deformation error.

Fig. 8 illustrates the RMS error of the intraoperative model built in different stages. According to the chart, as the number of frames scanned by ultrasound increases, the RMS error of intraoperative model decreases, which fits qualitative conclusion found in Fig. 6 and 7. When all 67 frames of ultrasound images were used, the RMS error of reconstructed surface is 1.68 mm, 6% less than the pre-acquired model. As more frames were collected and more area of the left atrium were scanned, the RMS error will be further reduced.

4. DISCUSSION, CONCLUSION, AND FUTURE WORK

In this work, a real phantom experiment method for evaluating a 3D surface modeling method is proposed. According to the results, the modeling method can improve the accuracy of the surface model because it makes use of intraoperative imaging data to update the pre-acquired data in two aspects. First, the RMS reconstruction error in the regions scanned and therefore updated by the intra-cardiac echocardiography is smaller than that of the regions without updating; and second, the more the frames of the intra-cardiac echocardiography were collected and used to update the pre-acquired model, the more accurate the updated model becomes. If contract vascular by 1mm and dilate the atrial body by 2mm, the least reconstruction error is 1.68mm when updating the preoperative model with all 67 frames ultrasound frames. This work demonstrates excellent promise for improved, real-time guidance of cardiac ablation procedures. In future, we will further evaluate the modeling method by carrying out animal test and finally apply our method in the catheter ablation therapy.

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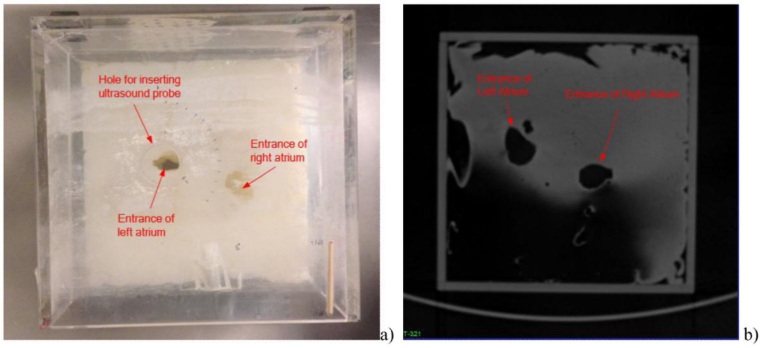

Figure 1.

Silicone atrial phantom. (a) The phantom fixed and immersed in a water bath. (b) One slice of CT scan showing the access ports of the atriums.

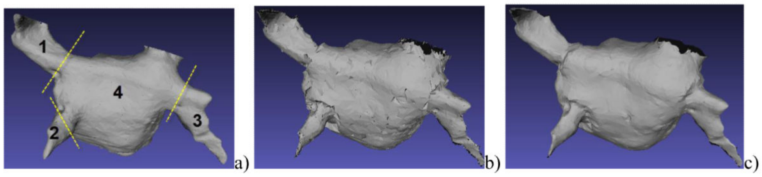

Figure 2.

Generation of simulated pre-operative model. (a) The atrial model was divided into four parts: pulmonary veins (1-3) and left atrium (4). Vertices of the pulmonary veins are contracted along its normal direction by 1 mm followed by a random dilation of the vertices of the left atrium along its normal direction by 2 mm. (b) The original model after deformation. (c) The deformed model after smoothing by Taubin Smooth Filter ($\lambda=0.5$, $\mu=-0.53$, smoothing steps=10) [4]

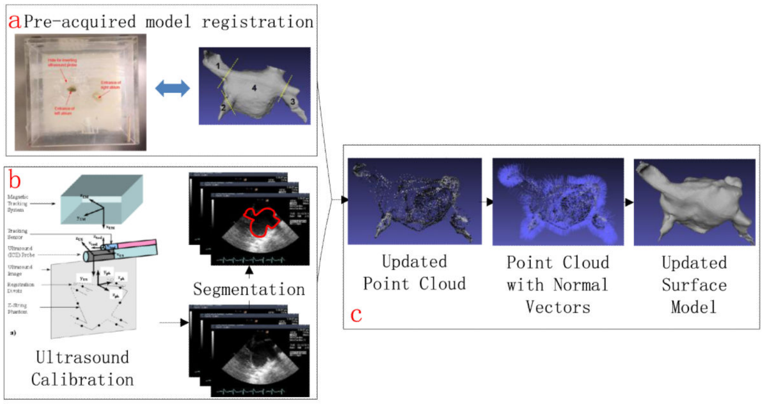

Figure 3.

Clinical workflow of the simulation experiment. The workflow is divided into three parts. (a) Pre-acquired model and phantom registration. (b) Ultrasound calibration and image segmentation. (c) Surface reconstruction.

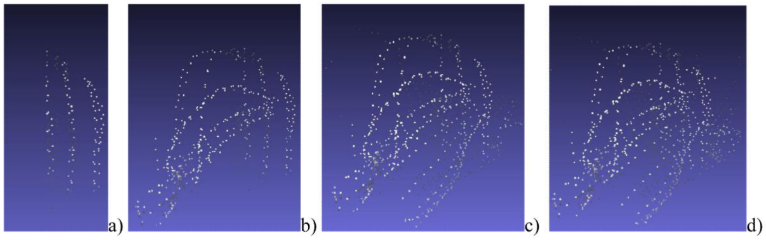

Figure 4.

Point cloud generated by segmented ultrasound images: (a) 10 frames collected; (b) 30 frames collected; (c) 50 frames collected; and (d) 67 frames collected.

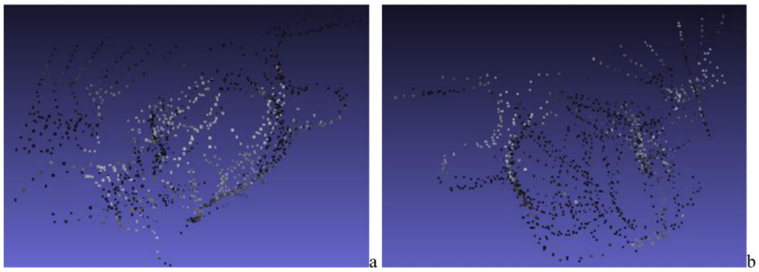

Figure 5.

Point cloud generated by segmenting 67 frames of ultrasound images viewed in two different views.

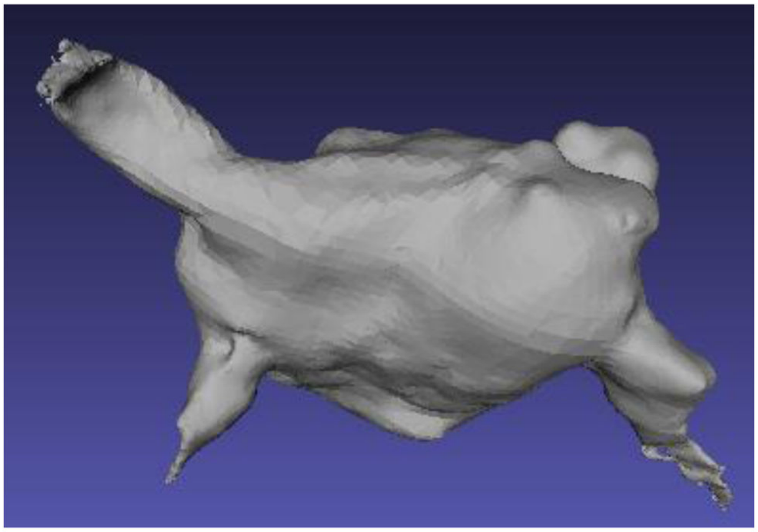

Figure 6.
The intraoperative model built by merging information from ultrasound and preoperative model.

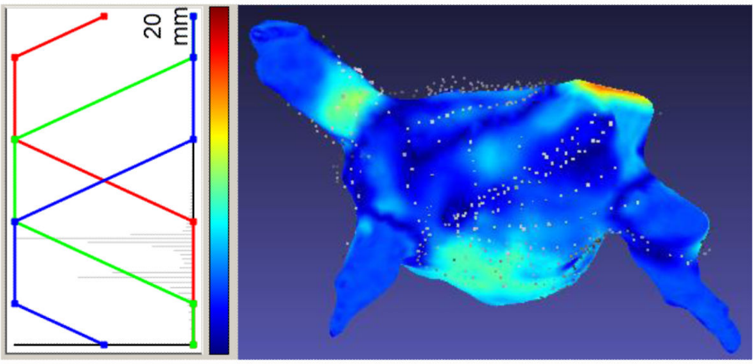

Figure 7.

The color map of reconstruction error. As color bar on the left shows, from blue to red, the reconstruction error increases. The white rectangles denote the intraopertative point cloud collected by ultrasound.

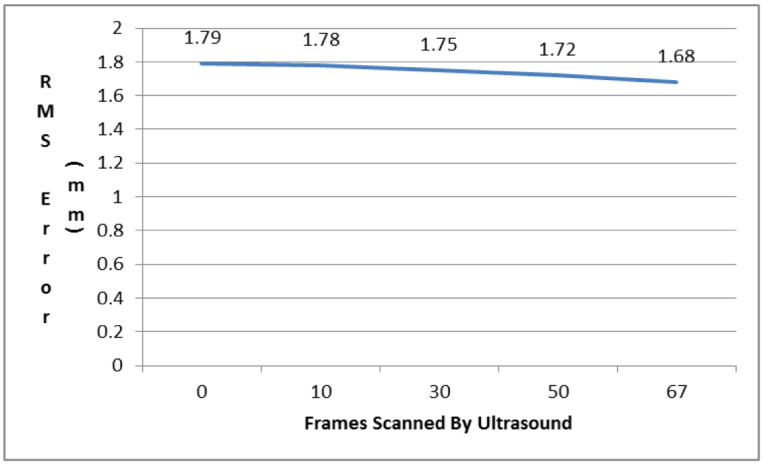

Fig.8.

Trend of RMS error as frames scanned by ultrasound increases.